Permeating Fluid Effects in Cellular Material Systems under Dynamic Loading

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Cellular materials come in myriad forms and serve an ever-increasing variety of engineering functions. Unfortunately, the basic research devoted to modeling the mechanical response of these materials largely has overlooked some of the most fundamental physical processes involved in the problems and applications of interest. Previous modeling efforts have focused almost exclusively on the mechanical response of the cellular solids, while essentially ignoring the evolving pressure and flow behavior of the gases and liquids permeating the intricate networks of cells that comprise such systems.

The primary objective of this work is to develop a new approach to modeling the dynamic response of cellular materials. The coupled physical response of both the cellular solids and the permeating fluids are considered, and the influence of the permeating fluid on the response of the cellular solid is investigated as the material deforms under dynamic loading [1].

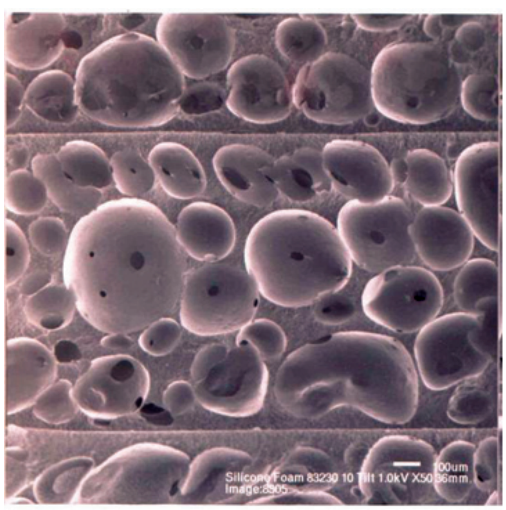

Fig. 1.
A scanning electron micrograph of a highly disordered, open-cell, silicone foam. Note the intricate structure at the cellular scale, the disordered nature of this structure, and the small apertures between cells. Micrograph provided courtesy of David J. Alexander, MST-6.

The new modeling approach couples the mechanical response of cellular solids with the physical behavior of the fluids permeating these materials through a multifield description of the governing equations of motion. Multifield theory is applicable when the average motion of one material in a multimaterial system is distinctly different from that of the other materials. The response of each material, therefore, is characterized by its own distinct velocity field, while the response of the overall cellular material system is governed by a set of coupled conservation equations.

Equations governing the conservation of mass, momentum, and energy are derived in multifield form using a traditional ensemble-averaging technique. Governing equations derived in this manner necessarily include additional momentum and energy source terms that arise through the averaging process. This set of coupled multifield equations is closed through the development of appropriate constitutive models for the resulting source terms [2].

The multifield approach has been used to simulate the response of highly disordered, open-cell, silicone foams to dynamic loading conditions using a conventional finite-volume computational algorithm, in which the multifield conservation equations are solved in the Lagrangian frame of the solid. The material of interest represents a relatively dense structural foam used primarily in the manufacture of stress cushions for use between much stiffer metallic parts in multicomponent engineering systems.

Simulations represent the first time that advanced constitutive models for cellular solids have been coupled with a physical representation of the associated permeating fluid behavior in a comprehensive continuum-scale response description for the overall cellular material systems. Results demonstrate that the permeating fluid can play a major role in the general response of cellular material systems, contributing to the overall load-carrying capacity of the materials and affecting rate dependence and signal propagation speeds.

Future research will focus on generalizing the multifield approach to include a more complete description of all relevant physical mechanisms occurring in both the fluid and solid fields. A more general description of the fluid field will be achieved through models that include terms for flow separation, viscosity induced shear stress, and turbulence induced Reynold's stress. Additionally, more general models for the cellular solid will be considered as well. Problems of interest include elastic wave propagation, low-frequency vibrations, sound wave attenuation, and strongly dynamic, shock-inducing phenomena.

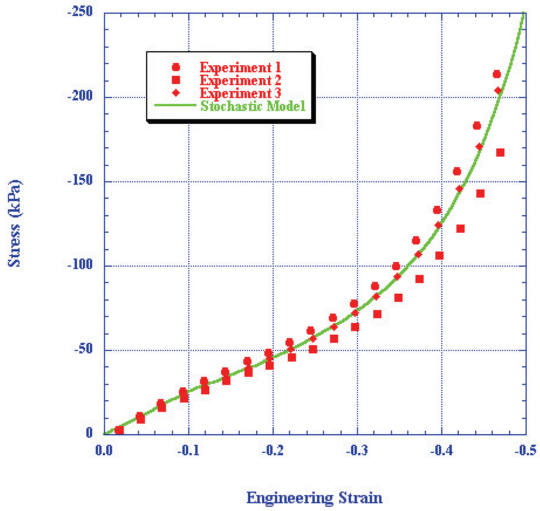

Fig. 2.
The continuum-scale stress-strain response of a silicone foam sample subjected to quasi-static uniaxial compression. Experimental results are plotted using solid data points and are shown for three different foam samples, each nominally possessing the same average material properties. Results obtained using the stochastic constitutive model are plotted using a solid line. Experimental data provided courtesy of Matthew W. Lewis, ESA-WR.

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[1] M.W. Schraad and F.H. Harlow, "A Multi-field Approach to Modeling the Dynamic Response of Cellular Materials," *Intl. J. Mech. Sci.* **48**, 85–106 (2006).
[2] M.W. Schraad and F.H. Harlow, "A Stochastic Constitutive Model for Disordered Cellular Materials: Finite-strain Uni-axial Compression," *Intl. J. Solids Structures*, in press (2005).

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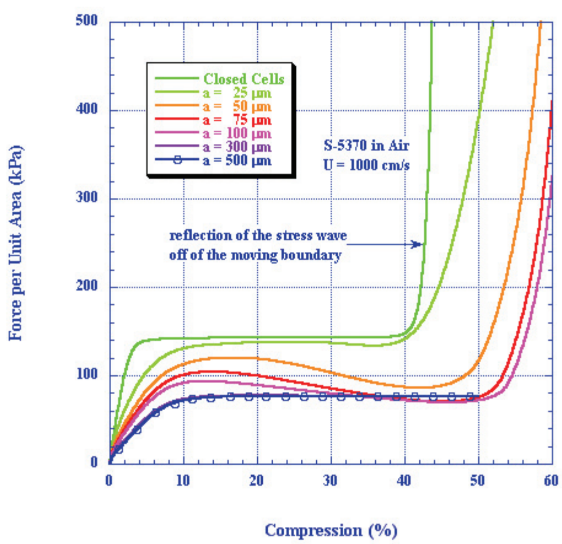

Fig. 3.
The total force per unit area plotted as a function of compression, illustrating the effect of average aperture size on the force required to deform the material. In general, as size increases, the force decreases, because the smallest apertures significantly restrict the flow of the permeating fluid, resulting in higher fluid pressures.